

Computer-Based Prediction of Personnel Injury Due to an Explosion

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ABSTRACT

In previous studies the High Explosive Damage Assessment Model (HEXDAM) and Vulnerability Assessment of Structurally Damaging Impulses and Pressures (VASDIP) software have been applied to a variety of problems dealing with blast damage assessment to structures. In many cases, however, the ultimate purpose of such studies has been the prevention of injury to personnel. Considerable data exist pertaining to the effects of blast on the human body but such data are generally in handbook-form, and are somewhat cumbersome to use. For this reason, based on experience gained in a recent court case involving a large explosives manufacturer, a research effort has been undertaken to develop software which is consistent with existing data concerning the effects of blast on the human body. The human body has been divided into 19 basic components, which include both bones and physiological systems. For each such component a scaled pressure-impulse diagram has been derived, and such P-I diagrams have been incorporated into the latest version of VASDIP. Both blast effects and whole-body displacement effects are taken into account. The vulnerability parameters suitable for use with HEXDAM are computed. Within HEXDAM the human body has been divided into seventeen structures, which are collectively referred to as the HEXDAM Man. Each such structure contains from one to three of the components (bones and/or physiological systems) contained in the latest version of VASDIP. The HEXDAM Man can be placed anywhere in a problem scenario in a wide variety of different poses or positions, forty-four of which are predefined. The user can also develop a virtually unlimited number of additional positions. Furthermore, there is no limit to the number of HEXDAM Men which can be added to a problem, each in a different location and position. The damage or injury resulting from an explosion is predicted for each component of each structure of each HEXDAM Man. Not only does HEXDAM Man provide a means of predicting injury to personnel, but also it provides a means by which the relative size of a structure or a facility can be readily visualized.

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1.0 INTRODUCTION

In their original form both the High Explosive Damage Assessment Model (HEXDAM) and the Vulnerability Assessment of Structurally Damaging Impulses and Pressures (VASDIP) software were designed to handle damage assessment for a wide range of structure types, composed of conventional (**inanimate**) building materials, exposed to an explosion [1-7]. In many cases, however, involving either safety or physical security, the primary concern is the potential for injury to personnel. Considerable experimental data exist pertaining to the effects of an explosion on the human body, but such data exist in the form of tables and/or curves in various handbooks, and are quite cumbersome to use [8-12]. During the course of a recent court case involving a large explosives manufacturer, the concept of the HEXDAM Man, consisting of seventeen **animate** structural components, was developed. Although originally introduced to provide an indication of the relative size of structures, the HEXDAM Man rapidly developed into a technique for predicting the injury to the various parts of the human body.

In addition to the HEXDAM Man concept, which has been incorporated into the HEXDAM software as described in section 2.0, three other related software packages have been developed. The MOVEMAN software, as described in Section 3.0, was designed to move the HEXDAM Man into an explosion scenario. The POSEMAN software, in similar fashion, was designed to allow the HEXDAM Man to be arranged in a variety of poses, as described in Section 4.0. As discussed in Section 5.0, to provide an accurate means of determining the vulnerability of various parts of the human body to explosive blast effects, the VASDIP Man software was developed. An example of the combined use of the four new software packages is presented in Section 6.0. Throughout this paper numbers within brackets refer to references cited, which are listed in Section 7.0.

2.0 HEXDAM MAN

The HEXDAM Man provides a means by which the relative size of a structure or facility can be readily established by comparison with the size of a human figure. Most of the users of the High Explosive Damage Assessment Model (HEXDAM) software, however, are concerned with personnel safety and the effects of an explosion on the human body. The HEXDAM Man can prove most useful in this respect when used with HEXDAM

5.0, which can handle structures stacked one on top of another [13]. Earlier versions of HEXDAM, which do not have this capability, cannot use the HEXDAM Man.

The HEXDAM Man consists of a collection of seventeen **external** and twenty-eight **internal** components, representing all the major parts of the human body, as shown in Figure 1. The external components simply represent structural containers within which the internal components are located. The HEXDAM Man can be placed anywhere in an existing problem scenario by means of MOVEMAN, as described in Section 3.0, in a number of different positions, as generated by POSEMAN, discussed in Section 4.0. Furthermore, there is no limit to the number of HEXDAM Men which can be added to a scenario. The probability of injury resulting from an explosion is predicted for each

NOTE: HEXDAM Man external components are in **bold print**.
 HEXDAM Man internal components are in *italics print*.

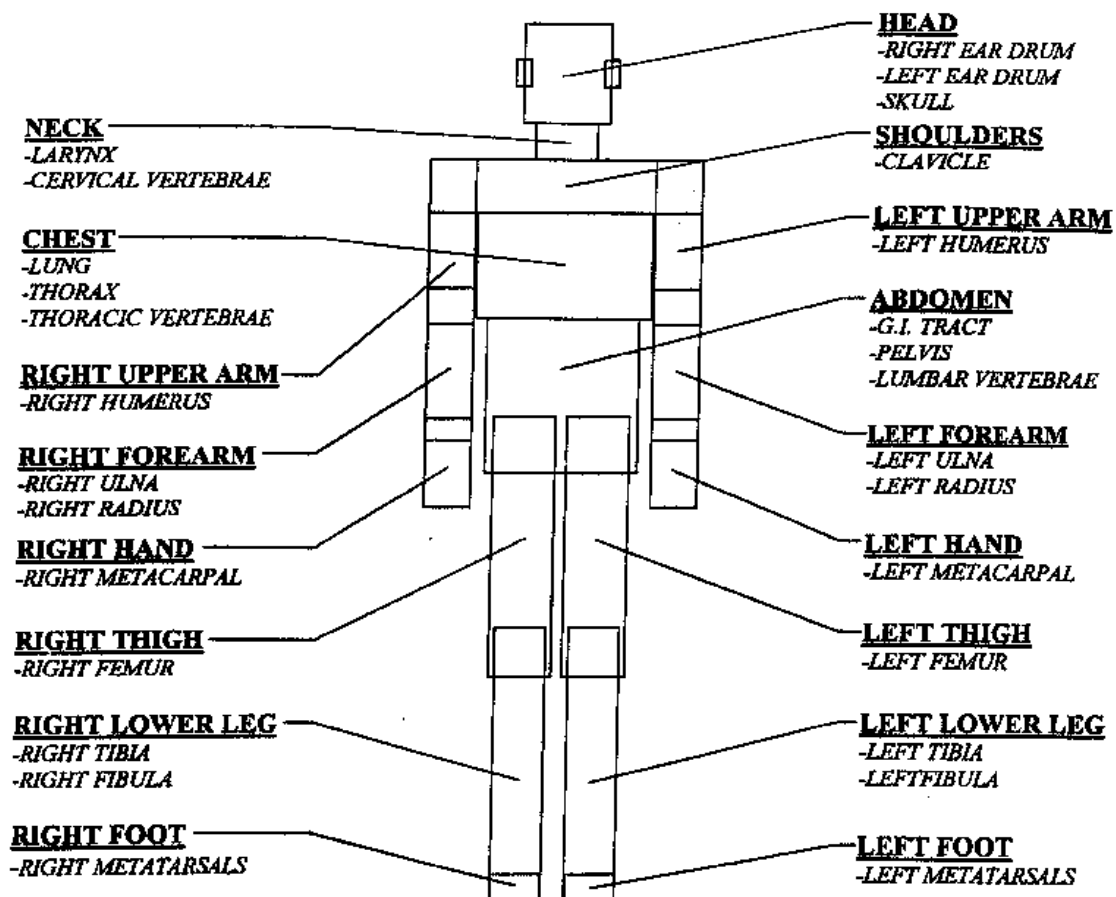


Figure 1. Internal Components within the External Components of the HEXDAM Man

internal component of each HEXDAM Man. Such predictions are based on the most accurate available data describing the vulnerability of the human body to blast, as generated by VASDIP Man, which is described in Section 5.0.

3.0 MOVEMAN

For each scenario described by the HEXDAM software, a Problem Data File must be developed [13]. Such a Problem Data File constitutes a description of a collection of structures, and in most cases, in its initial form, includes only structures representing inanimate objects. In such situations structures representing the **external** components of human bodies, consistent with HEXDAM Man, can be added to the scenario by means of the MOVEMAN software routine.

By means of MOVEMAN, the external HEXDAM Man, in any position, as contained in a special Problem Data File, can be introduced into a scenario at any location, facing any direction. Furthermore, an unlimited number of external HEXDAM Men can be added in this manner. The final result is an expanded Problem Data File containing the original inanimate structures, plus the human structures, represented by the external HEXDAM Men. In similar fashion the MOVEMAN software routine can be used to add structures, representing the **internal** components of the HEXDAM Man. In any situation where prediction of injury is required, the **internal** HEXDAM Man should be used, as opposed to the **external** HEXDAM Man.

Before moving the HEXDAM Man into a particular explosion scenario, some adjustment to his pose may be appropriate. Such adjustments can be accomplished by means of POSEMAN, discussed in Section 4.0.

4.0 POSEMAN

A special Problem Data File, containing seventeen **external** components, comprising the **external** HEXDAM Man in a standing position, constitutes the basic description of the **external** HEXDAM Man. By means of the POSEMAN software this basic position can be modified to produce a number of other positions. In this manner, Problem Data Files have been generated for the forty-four predefined positions, as shown in Figure 2. The basic standing position previously noted corresponds to Position #1 in the figure. In

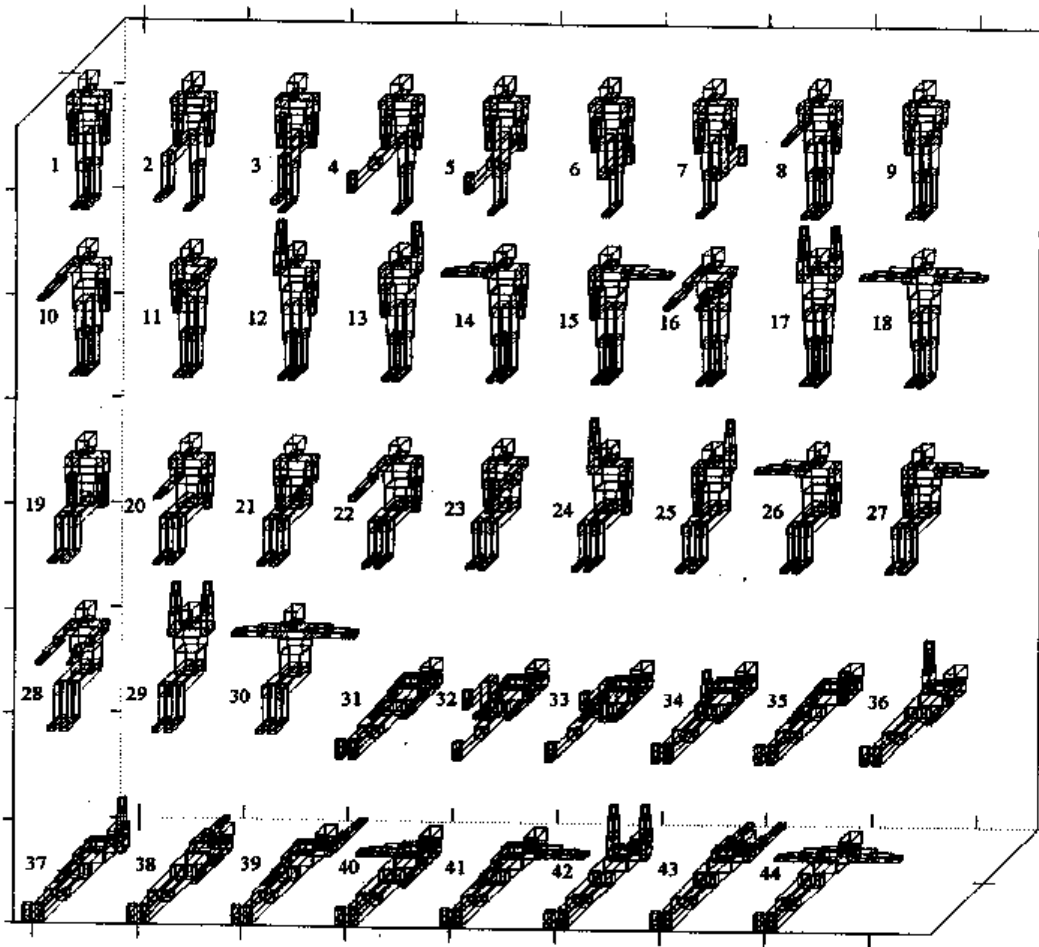


Figure 2. Predefined Positions of HEXDAM Man

addition, by means of POSEMAN the user can generate a variety of other positions for the external HEXDAM Man.

The POSEMAN software allows the user to change the external HEXDAM Man's position by bending his joints in a manner generally consistent with the actual bending capabilities of the human body. The bending angles are, however, limited to integer multiples of 90° .

In cases involving prediction of injury, the **internal** HEXDAM Man should be used. A special data file containing nineteen internal components, corresponding to the nineteen components of VASDIP Man described in Section 5, constitutes the basic description of the internal HEXDAM Man. Nine of these internal components occur twice,

corresponding to the left and right sides of the body. Thus, the internal HEXDAM Man **actually consists of** twenty-eight components. The relationship between the external and internal components of the HEXDAM Man and the components of VASDIP Man are shown in Table 1.

The POSMAN software arranges the twenty-eight internal components of the HEXDAM Man so that they coincide with the appropriate external components of the HEXDAM Man for any selected pose. In effect, POSMAN uses the seventeen external components of HEXDAM Man to generate a specific position, and then introduces each of the twenty-eight internal components into the appropriate external components.

Table 1. Relation Between HEXDAM Structural Components and VASDIP Man Body Components		
HEXDAM Man		
<u>External Components</u>	<u>Internal Components</u>	<u>VASDIP Man Components</u>
Head	Right Eardrum	Eardrum
	Left Eardrum	Eardrum
	Skull	Skull
Neck	Larynx	Larynx
	Cervical Vertebrae	Cervical Vertebrae
	Lungs	Lungs
Chest	Ribs	Ribs
	Thoracic Vertebrae	Thoracic Vertebrae
	G.I. System	G.I. System
Abdomen	Pelvis	Pelvis
	Lumbar Vertebrae	Lumbar Vertebrae
Right Upper Arm	Right Humerus	Humerus
Right Forearm	Right Ulna	Ulna
	Right Radius	Radius
Right Hand	Right Metacarpals	Metacarpals
Left Upper Arm	Left Humerus	Humerus
Left Forearm	Left Ulna	Ulna
	Left Radius	Radius
Left Hand	Left Metacarpals	Metacarpals
Right Thigh	Right Femur	Femur
Right Lower Leg	Right Fibula	Fibula
	Right Tibia	Tibia
Right Foot	Right Metatarsals	Metatarsals
Left Thigh	Left Femur	Femur
Left Lower Leg	Left Fibula	Fibula
	Left Tibia	Tibia
Left Foot	Left Metatarsals	Metatarsals

5.0 VASDIP MAN

As noted in Section 2.0, the HEXDAM Man has recently been developed to provide means for applying the HEXDAM software to the prediction of injury to personnel. In order to produce realistic results with HEXDAM, however, accurate vulnerability parameters must be assigned to each of the twenty-eight internal components which make up the internal HEXDAM Man. With this point in mind, the VASDIP Man has been designed for incorporation into the VASDIP software to provide a means of calculating such vulnerability parameters.

Vulnerability data for certain components of the human body are available in the form of pressure-impulse diagrams, as well as overpressure tables [8-12]. In addition to such data, the strength of most major bones in the human body can be derived from medical texts [14-16]. Based on these data sources, vulnerability parameters can be developed for fifteen bone types and four (soft-tissue) body systems, as indicated in Table 2.

The comparison of the nineteen body components of the VASDIP Man with the seventeen **external** components and the twenty-eight **internal** components, comprising the HEXDAM Man shown in Table 1, reveals that each HEXDAM Man internal component corresponds to one

Table 2. Body Components for Which Vulnerability Parameters Can Be Calculated

<u>Component</u>	<u>Vulnerability Data Source</u>	<u>Sensitivity Type*</u>
Eardrums	8,9,12	P
Skull	8,9,12	Q
Larynx	8	P
Cervical Vertebrae	14	Q
Clavicle	14	Q
Lungs	8,9,12	P
Ribs	14	Q
Thoracic Vertebrae	14	Q
G.I. System	8	P
Pelvis	14	Q
Lumbar Vertebrae	14	Q
Humerus	14	Q
Radius	14	Q
Ulna	14	Q
Metacarpals	15,16	Q
Femur	14	Q
Fibula	14	Q
Tibia	14	Q
Metatarsals	15,16	Q
* "P" denotes overpressure sensitive		
"Q" denotes dynamic pressure sensitive		

VASDIP Man body component. Thus, for each HEXDAM Man internal component there exists one set of vulnerability parameters, as calculated by VASDIP Man.

As noted in Table 2, the four soft-tissue components are classified as "P"-type structures, because of their sensitivity to overpressure. Pressure-impulse diagrams derived from experimental data [17-19] have been developed for each such component. An example of such a diagram, generated by VASDIP Man, for the lungs of a 180-pound man is given in Figure 3. This diagram agrees well with the diagram produced by Baker, et al. [12, 20], which more closely conforms to the experimental data than the diagram produced by Mercx [9]. Similar diagrams have been developed for the other three soft-tissue components of the VASDIP Man.

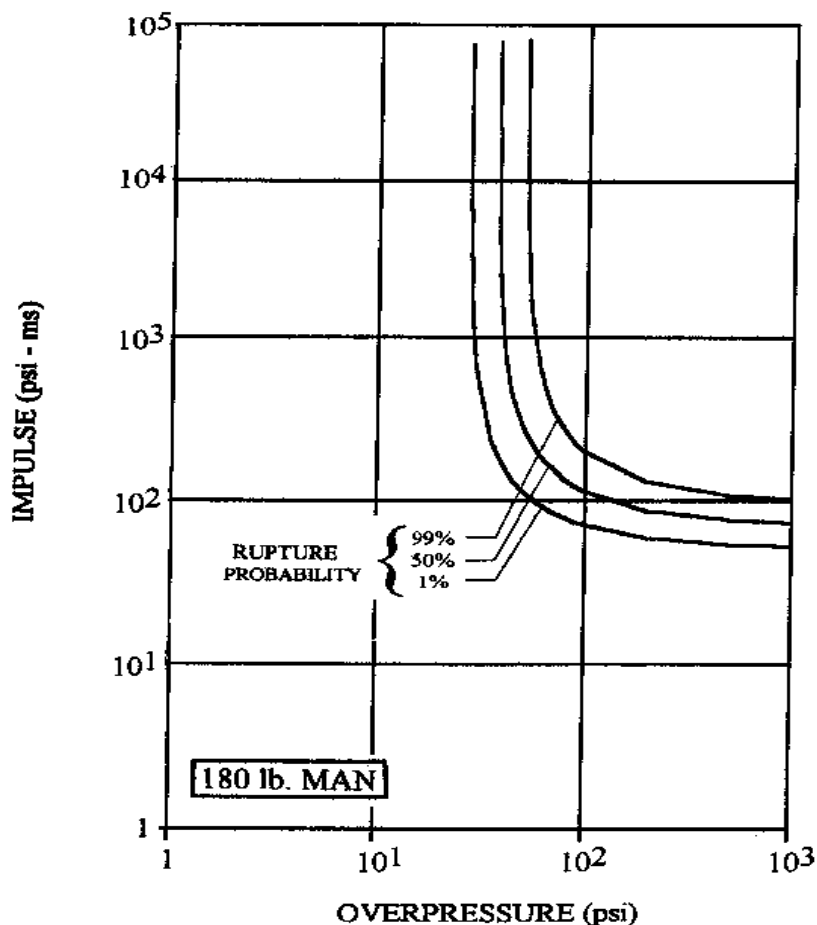


Figure 3. Pressure-Impulse Diagram for Human Lungs
According to VASDIP Man

As indicated in Table 2, the fifteen bone components of the VASDIP Man are "Q"-type structures because of their sensitivity to dynamic pressure. Such dynamic pressure, (or more properly the drag), resulting from the passage of the blast wave, acting on the human body will cause the body to be swept along behind the wave at some displacement velocity. Injuries occur when the body in motion encounters a stationary, solid structure. The displacement velocities

associated with various injury levels to the skull and the whole body have been previously established [21-23]. By solving the equation of motion for a body immersed in a transient flow field, the displacement velocity can be computed as a function of peak

overpressure and impulse. This computation has been previously attempted by Baker, et al. [20] and by Mercx [9]. In each case, however, significant deficiencies in the computation occurred.

In Baker's analysis of the human skull, both diffraction pressure loading and drag loading were computed, but the drag on the human body was based on the dynamic pressure exerted on a stationary object, with no adjustment for the motion of the object. As a result, as indicated in Figure 4, some of the displacement velocities calculated by Baker exceeded the particle velocity behind the blast wave, which is physically impossible. Because of this deficiency Baker's curves at lower peak overpressures ($< .4$ psi) are very inaccurate.

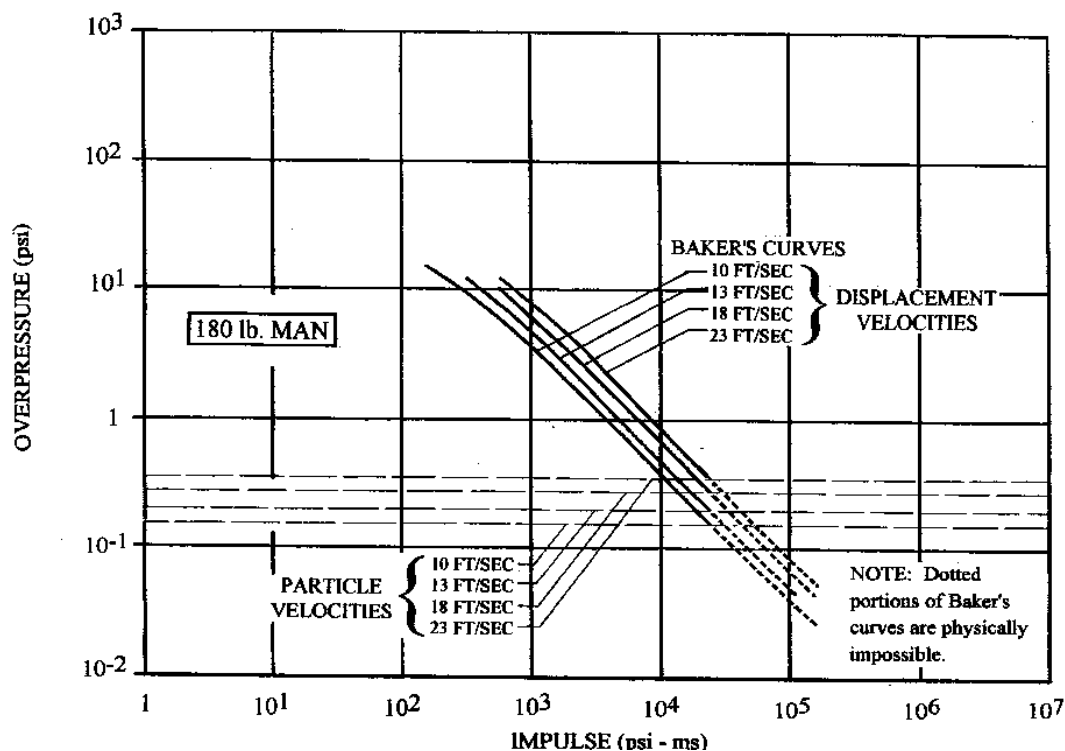


Figure 4. Pressure-Impulse Diagram for Human Skull According to Baker, et al. [20]

In Mercx's analysis of the human skull the effect of diffraction pressure loading was neglected. In addition, in calculating the particle velocity behind the blast wave, Mercx used the ambient air density instead of the air density behind the blast wave [24]. These two deficiencies cause considerable inaccuracy in Mercx's work at overpressures above approximately 10 psi.

In the current analysis the effects of both diffraction pressure-loading and drag-loading were considered, with the displacement velocity of the body taken into account, and with the correct air density used in the particle velocity equation. The drag coefficient for the human body was set equal to 1.3 [25]. The resulting pressure impulse diagram, corresponding to a displacement velocity of 18 feet per second, is presented in Figure 5 for a 180-pound man. For purposes of comparison the corresponding curves based on Baker and Mercx are included in the figure. At low pressures the curve generated by the current study closely matches that of Mercx and, as expected, lies well above Baker's curve. At pressures between 3 and 10 psi the curve of the current study generally agrees with Baker's curve, as Mercx's curve drifts to the right. The current curve extends to pressures as high at 1000 psi, while Baker's curve ends at ~10 psi, and Mercx's at ~100 psi.

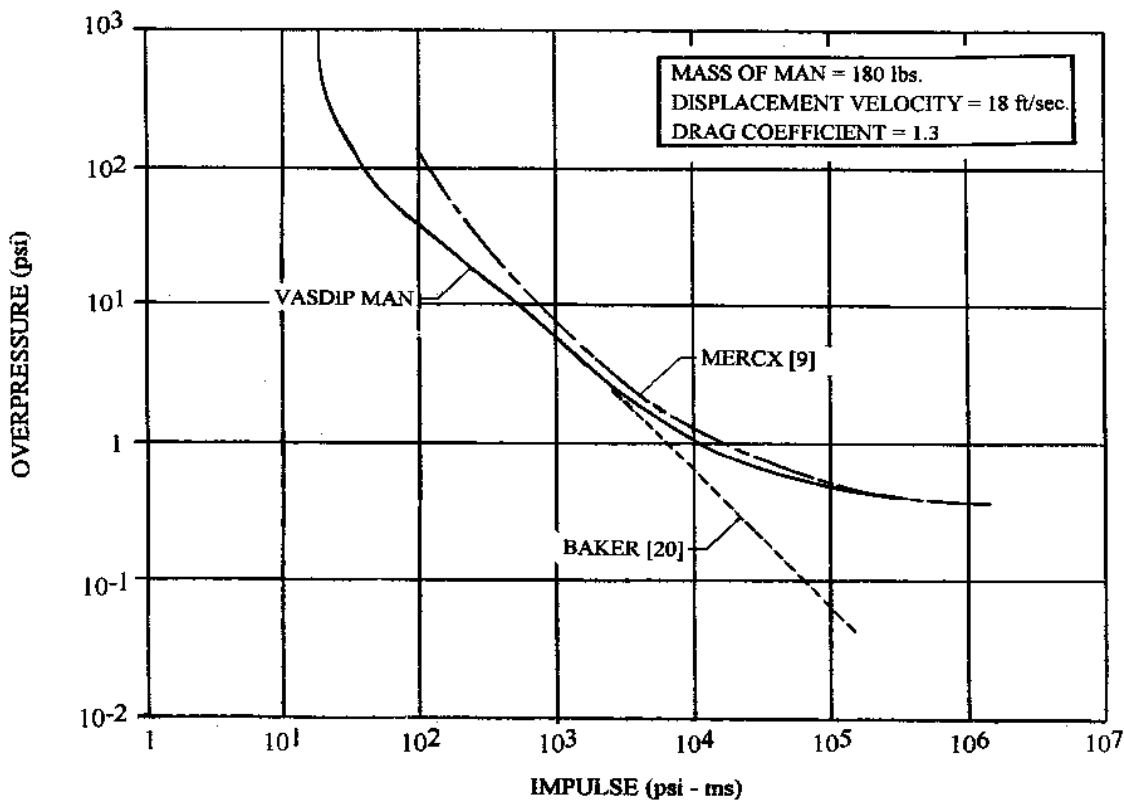


Figure 5. Comparison of Pressure-Impulse Plots for Human Skull

Based on the more accurate analysis associated with the current study the pressure impulse diagrams for the skull representing displacement velocities of 10, 13, 18 and 23 feet per second are presented in Figure 6. These velocities correspond to injury probabilities of 0, 1, 50 and 99%, respectively. Based on the work of Messerer [14],

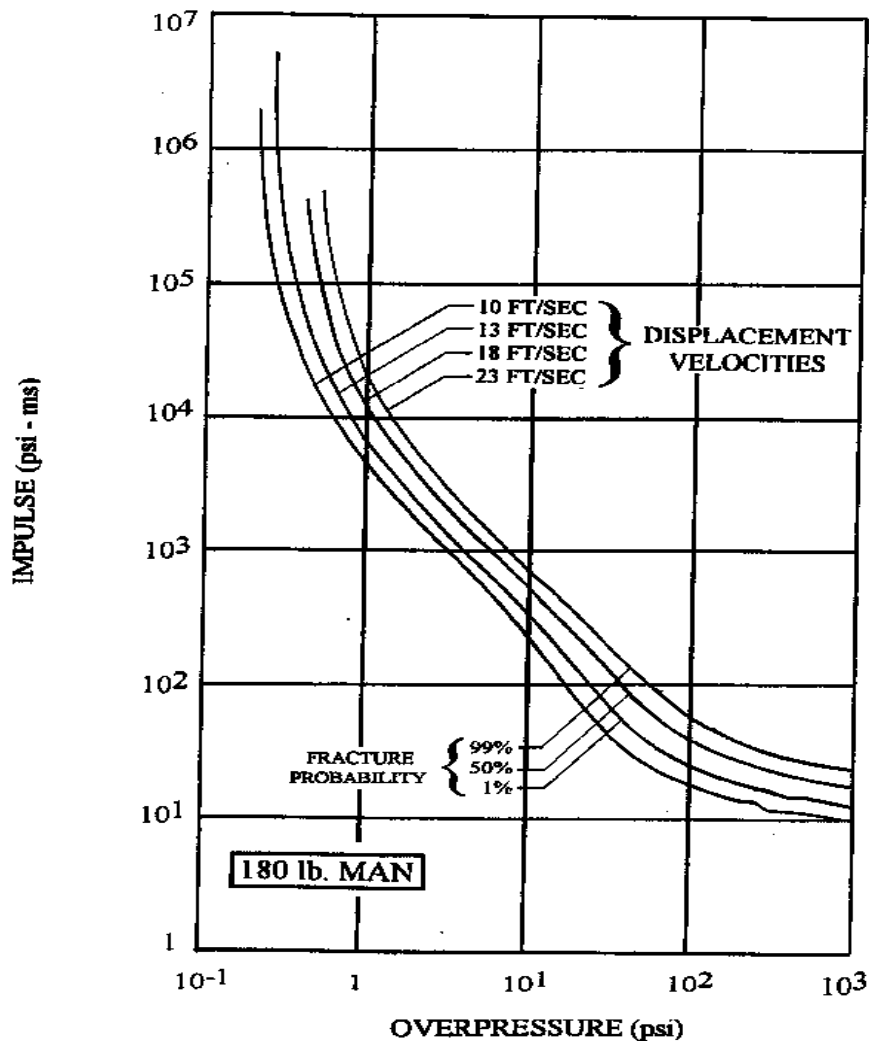


Figure 6. Pressure-Impulse Diagram for Human Skull According to VASDIP Man

Evans [15], and Hamilton [16], in similar fashion the pressure-impulse diagrams for the other fourteen bone type have been generated for the VASDIP Man.

6.0 EXAMPLE PROBLEM

As a demonstration of the combined utilization of HEXDAM Man, MOVEMAN, POSEMAN, and VASDIP Man, an explosion scenario has been generated involving one structure and eight individuals, as depicted in Figure 7.

Outside the building, at a distance of 17.25 feet, an explosive charge of 100 pounds of TNT is detonated at ground level.

In constructing this scenario the original Problem Data File, for use in HEXDAM 5.0, consisted of the empty building. By means of MOVEMAN the eight HEXDAM Men were added to the Problem Data File. Consistent with Figure 2, the man at the door was assigned predefined pose #08, while the man at the window was assigned pose #10. Two of the men seated at the table were assigned pose #20 while the other two were assigned #22. The two men outside the building were assigned special poses generated by

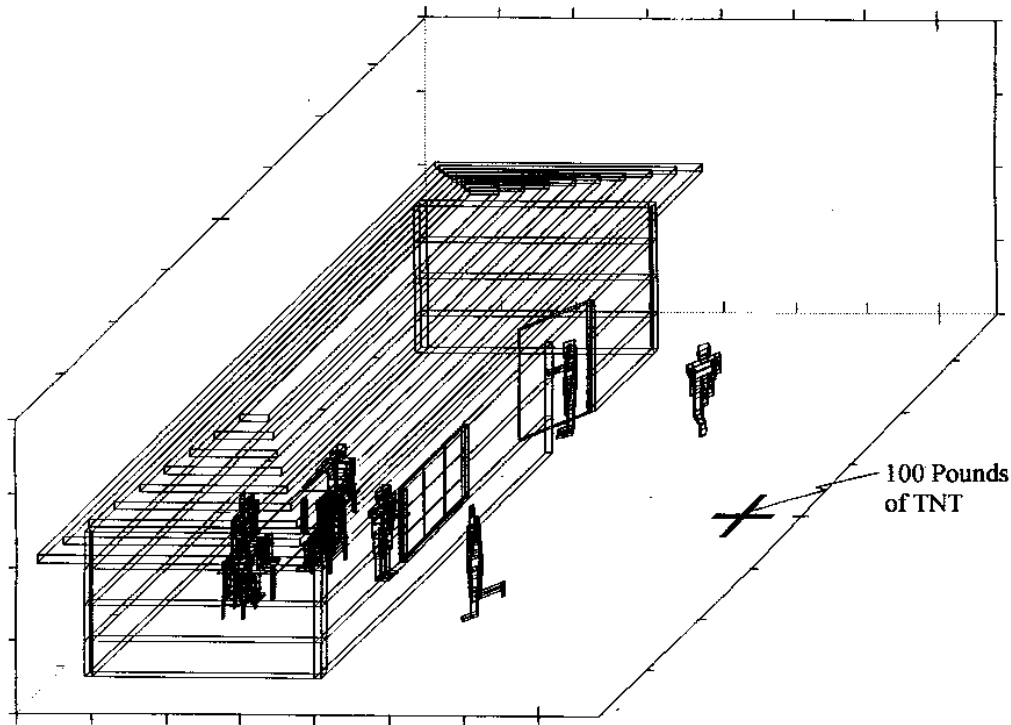


Figure 7. Scenario for Example Problem

POSEMAN. The vulnerability parameters for the internal components of each man were obtained from VASDIP Man.

A sequence of overpressure contour plots for the scenario, as generated by HEXDAM 5.0, are shown in Figures 8a through 8h. The injuries predicted for the HEXDAM Man, pointing out the window in Figure 7, are depicted in Figure 9. Such injuries would generally be considered to be fatal. It is interesting to note that the major injuries are confined to those parts of the HEXDAM Man's body exposed to the blast through the window, the lower part of his body being shielded by the portion of the building wall beneath the window, as shown in Figure 10.

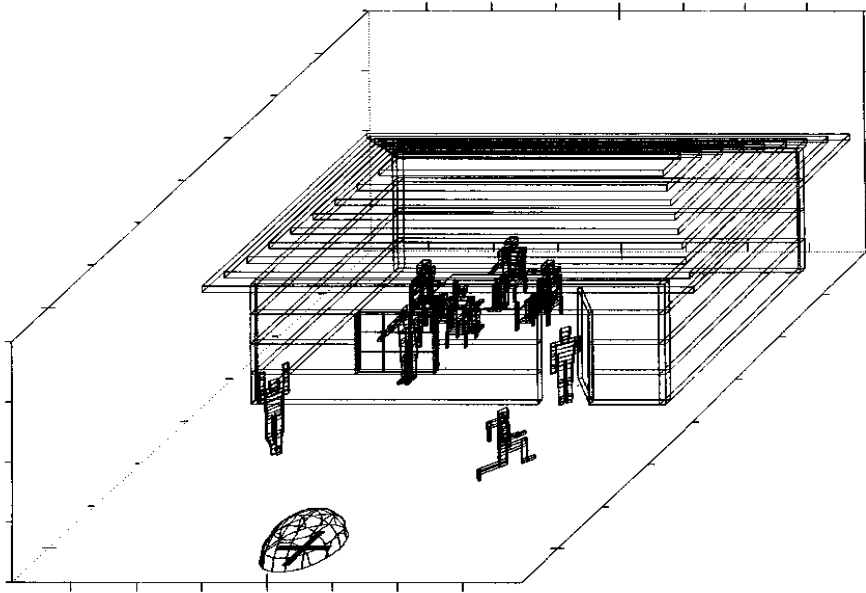


Figure 8a. Overpressure (2000 psi) Contour Plot for Example Problem

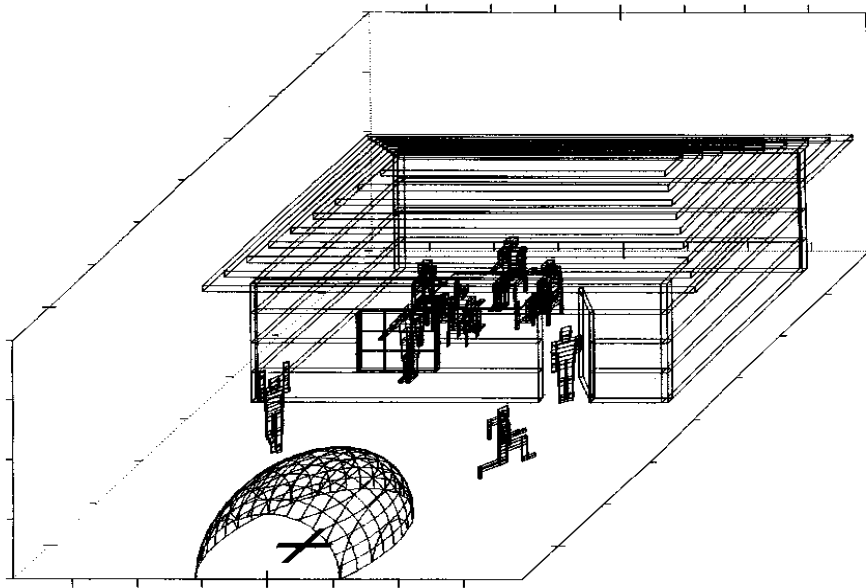


Figure 8b. Overpressure (500 psi) Contour Plot for Example Problem

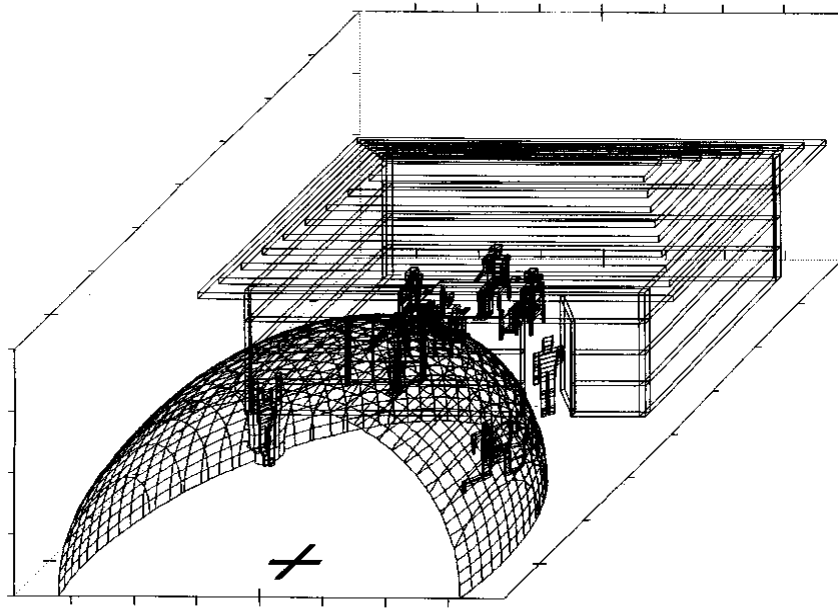


Figure 8c. Overpressure (100 psi) Contour Plot for Example Problem

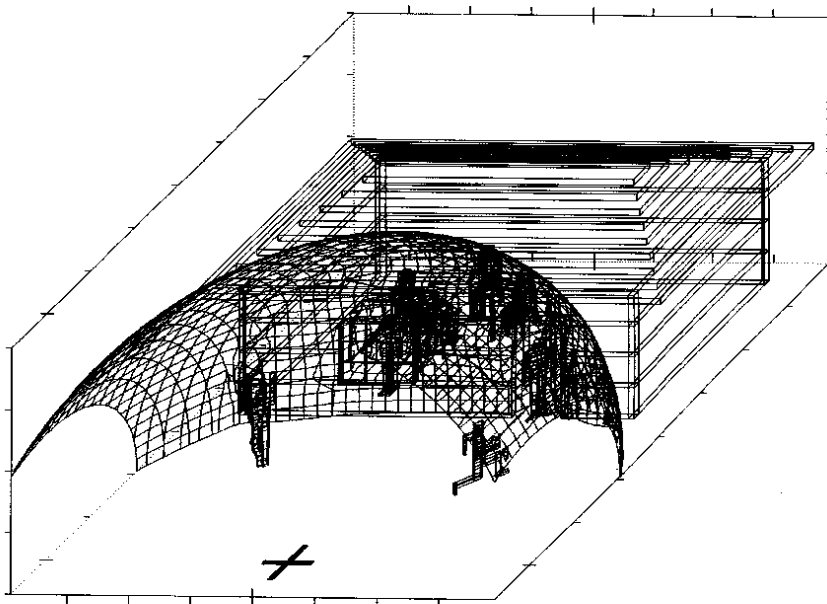


Figure 8d. Overpressure (50 psi) Contour Plot for Example Problem

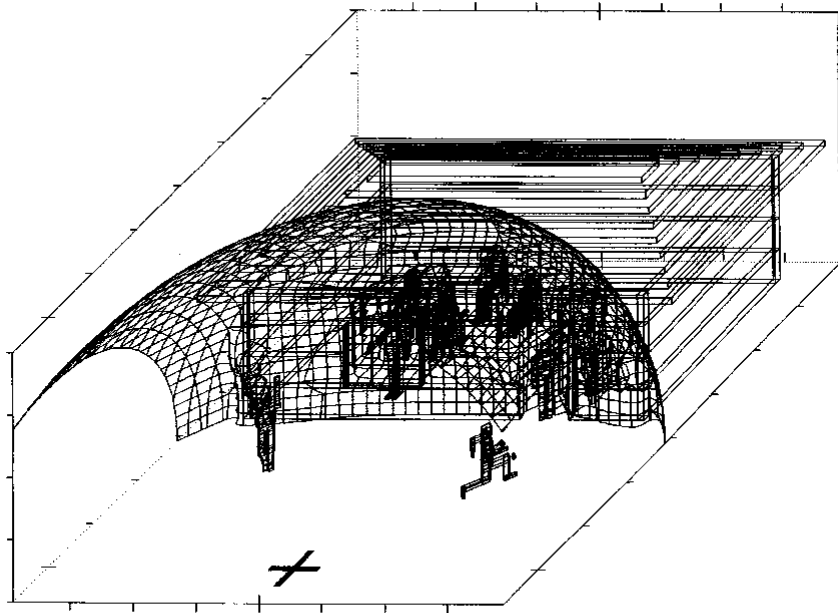


Figure 8e. Overpressure (40 psi) Contour Plot for Example Problem

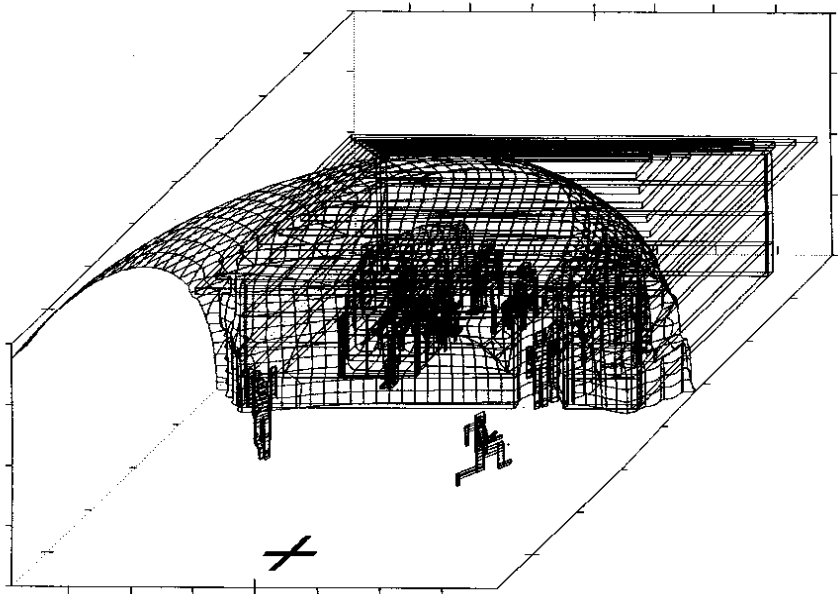


Figure 8f. Overpressure (30 psi) Contour Plot for Example Problem

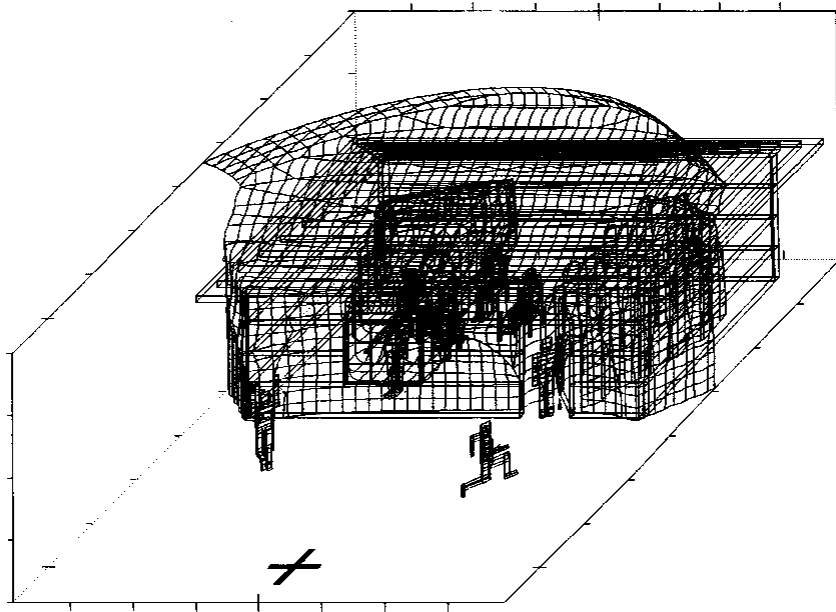


Figure 8g. Overpressure (20 psi) Contour Plot for Example Problem

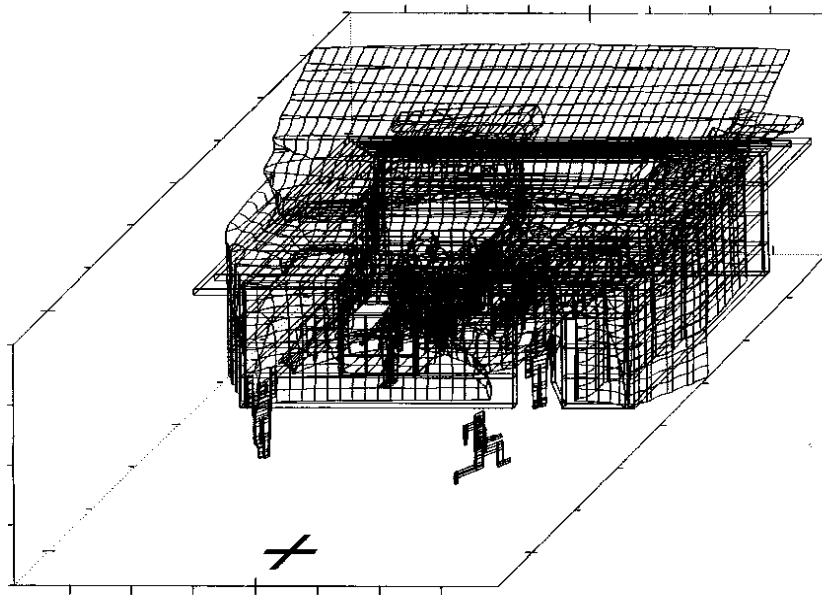


Figure 8h. Overpressure (10 psi) Contour Plot for Example Problem

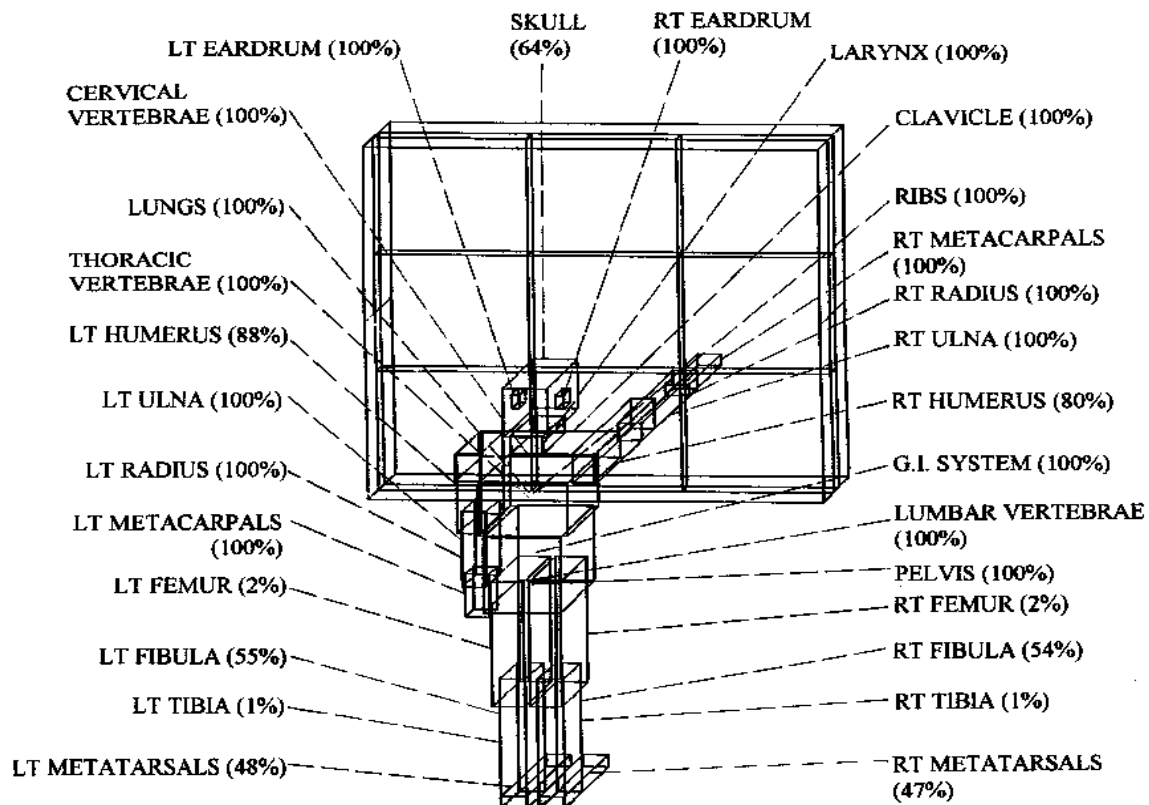


Figure 9. Predicted Injuries to HEXDAM Man Pointing Out Window in Example Problem

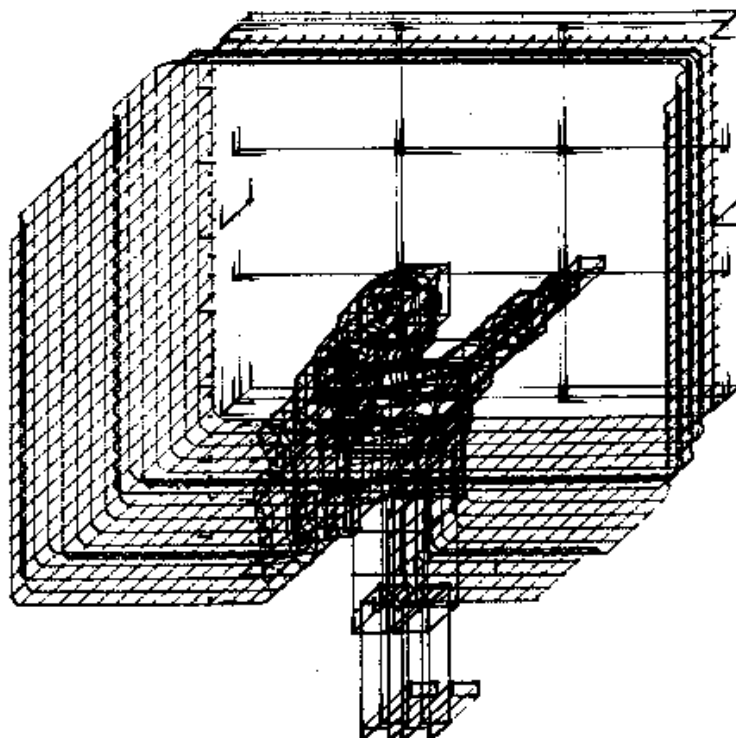


Figure 10. Overpressure (30 psi) Contour Plot in Vicinity of HEXDAM Man Pointing Out Window in Example Problem

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